Primer

Climate and climate change

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The Earth's climate system at fine spatial and temporal scales is chaotic, with evolving weather patterns often notoriously difficult to predict very far in advance. At regional scales, surface conditions are modulated by seasonal to decadal oscillations in surface temperature, precipitation, sea-ice extent, and ocean upwelling. However, 'climate', which in essence is the statistics of weather on time-scales of a few decades or more, is relatively well behaved and predictable. Indeed, over the past few thousands years and up until the time of the Industrial Revolution (ca. year 1765), global mean surface air temperatures have rarely varied by more than about ±0.5°C and atmospheric CO_2 by not more than ±4 ppm. Today's species and ecosystems are adapted to these environmentally stable conditions. It is this quasi-equilibrium state of climate and life that we are now disrupting, with a rate and magnitude of increase in greenhouse gases such as CO_2, CH_4 and N_2O that exceeds anything observed in at least the past 800,000 years. The speed at which the climate system will respond to this forcing, both in the global mean state as well as the frequency and magnitude of regional climatic extremes, will pose serious challenges for species and ecosystems and may exceed their ability to migrate and adapt. This Primer provides a brief introduction to the nature and workings of the climate system and its response to human perturbation.

The Earth's climate

The Earth absorbs solar radiation, primarily in visible, near infra-red (IR) and ultra-violet (UV) wavelengths (Figure 1). The shape of the planet creates a progressive reduction in incident solar energy per unit area towards higher latitudes as the surface becomes more oblique with respect to the Sun's rays. The tilt of the Earth's axis of rotation compared to the plane of its orbit around the Sun evens out the annual distribution somewhat, such that the solar energy at the top of the atmosphere is about 417 W m^{-2} at the equator, 237 W m^{-2} at a latitude of 60°, and dropping to 173 W m^{-2} on average at the poles. Equally important for climate is the seasonal redistribution of absorbed solar energy as the Earth orbits around the Sun. The Earth's spin–axis alignment, angle and circularity of orbit are modulated on long time-scales with important periodicities at ~21, 41, 100, and 413 thousand years, which pace the coming and going of ice ages over the past few million years.

Not all incident solar energy is absorbed — the Earth's surface is very variable in how much is absorbed and how much reflected. The reflectivity to solar wavelengths, called 'albedo', varies from as high as 0.8–0.9 (80–90% reflected) for fresh snow, around 0.4 for desert sand, to as low as ~0.1 for bare, wet soil. Plants play a key role here, as the albedo of the leaf canopy typically lies in the range 0.15–0.25 — higher than bare soil, but lower than desert or snow-covered ground. Clouds intercept a proportion of solar radiation before it can reach the surface, with an albedo in the range ~0.4 to 0.7 depending on cloud type. Clouds can also 'recycle' light not absorbed at the surface and re-direct it back downwards. The generally more extensive cloud cover at higher latitudes more than halves the annual solar energy reaching the surface, which, together with the permanent and seasonal presence of high albedo snow and ice, amplifies the disparity in absorbed energy between poles and equator to something approaching an order of magnitude.

On a global average, about 26% of the total incoming solar energy is reflected by clouds, with the rest mostly absorbed at the surface. This is important because it means that the atmosphere is primarily heated from below and it is this that fuels the rich and complicated behavior

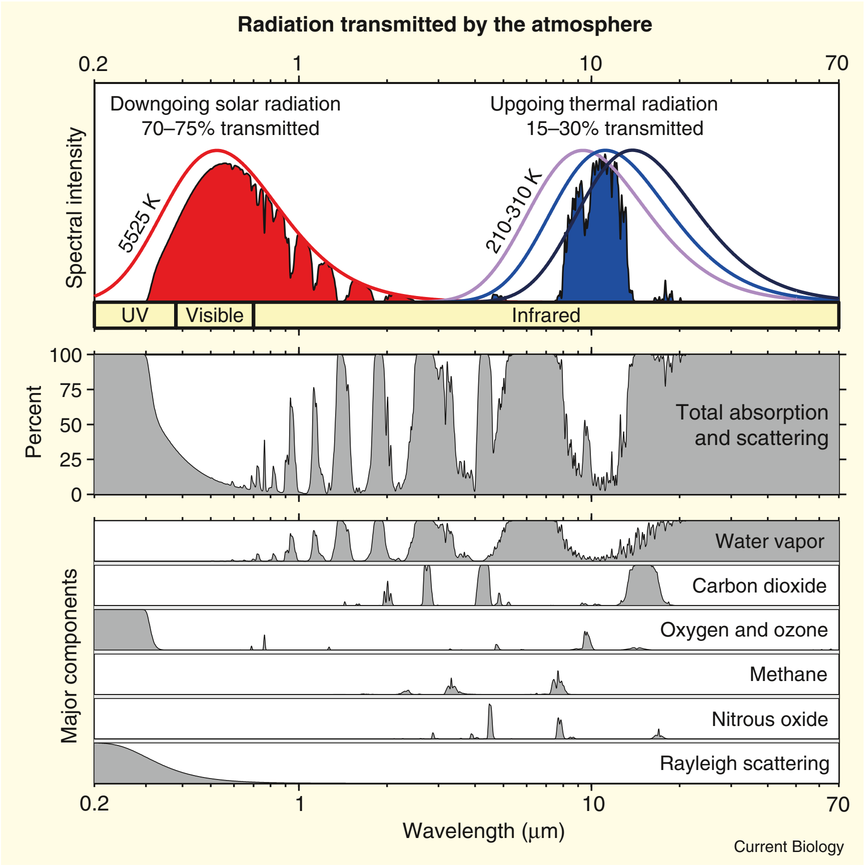

Figure 1. Greenhouse gases.

The pattern of absorption bands generated by various greenhouse gases and aerosols (lower panel) and how they impact both incoming solar radiation (upper left) and outgoing thermal radiation from the Earth's surface (upper right). (Figure prepared by Robert A. Rohde for the Global Warming Art project.)

of the climate system. Key to this is convection — air heated by a warm underlying surface becomes buoyant and rises, redistributing energy vertically, both through the elevated temperature of the air itself (sensible heat) and by carrying water in its vapor phase (latent heat). Latent heat energy is released when clouds form and the moisture returns to the surface in its lower energy liquid state as rain (and snow). Convection is particularly important at tropical latitudes, as well as seasonally and more locally in the form of thunderstorms elsewhere. The large-scale circulation of the ocean is, in some respects, a mirror image of the atmosphere — wintertime cooling of the surface at relatively high latitudes can make seawater denser at the surface than below it, leading to instability and convection downwards, powering circulation of the deep ocean. The rejection of dense brines during sea-ice formation also facilitates the production of deep water masses and deep circulation.

Movement in the ocean and atmosphere is modulated by the rotation of the Earth according to the Coriolis Effect — the deflection of winds and currents to conserve angular momentum, as well as by secondary influences such as topography, for instance the diversion of the high altitude jet stream in the atmosphere by the Rocky Mountains. In the ocean, surface wind-driven circulation patterns are important in transporting and redistributing heat energy, with the warm 'Gulf Stream' current from low latitudes to the North Atlantic providing a seasonal warming of up to 10°C in places.

The greater heat capacity of the ocean surface compared to land has important effects; for example, it keeps coastal areas warmer in the winter than the continental interiors. Phenomena such as monsoons arise from seasonal contrasts between land and sea surface temperatures caused by the lag in warming of the ocean such that the land surface is hotter. Coastal breezes are a related, but more local-scale and diurnal consequence of time-varying solar heating and the differing heat capacities of land and sea. Quasi-periodic phenomena such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) involve complicated interactions between atmosphere and ocean, and may also involve the presence of internal instabilities within the climate system. Some of these features may be partially predictable (leading to the possibility of seasonal forecasts), whereas other aspects are chaotic.

CO_2 and the 'greenhouse effect'

To balance the absorbed shortwave solar energy, subsequently re-distributed by ocean and atmospheric circulation, the Earth must continually radiate energy to space, which for a typical terrestrial planet occurs mostly in the infra-red (Figure 1). To escape the Earth, however, IR radiation originating at the land and ocean surface must pass through the atmosphere. Water droplets and clouds impede its progress upwards by absorbing and re-radiating energy. More important is the presence of gas molecules that are capable of undergoing changes in the degree of asymmetry of their electric field when they vibrate, which allows interaction with electromagnetic radiation at IR wavelengths. Such gases include water vapor (H_2O), CO_2, CH_4 and N_2O, as well as certain industrial compounds (such as chlorofluorocarbons, 'CFCs'). Completely symmetric molecules such as O_2 and N_2, which make up 99% of the Earths atmosphere, do not contribute to the energy balance of the Earth. Much of the IR spectrum is already effectively blocked by the presence of water vapor, the most important naturally occurring greenhouse gas. However, there are important 'window' regions in the spectrum, particularly between about 8 and 15 μm (Figure 1), through which IR radiation can escape to space. The presence of CO_2 in the atmosphere is important because one of the frequencies it absorbs most effectively at sits right up against this window — adding more CO_2 into the atmosphere broadens this absorption peak, narrowing the width of the window and hence blocking the escape of IR radiation. The frequency bands at which CH_4 and N_2O absorb at are said to be less saturated than CO_2, meaning that they are much more potent IR absorbers than CO_2 molecule-for-molecule. However, their relative concentrations in the atmosphere are much lower: only ~0.5% for CH_4 and ~0.1% for N_2O compared to CO_2.

Although IR active gas molecules re-radiate the energy absorbed, it is emitted in all directions, including back downwards. Hence, the presence of gases such as CO_2 in the atmosphere makes the overall process by which the Earth's surface can lose heat less efficient, resulting in a warmer surface. This process is what is known as the 'greenhouse effect', although this is something of a misnomer because greenhouses work primarily by preventing the convective loss of sensible and latent heat energy. It is important to recognize that the presence of a greenhouse effect on Earth is a natural phenomenon. Simple energy budget calculations show that the average surface temperature of the Earth in the absence of IR active gases in the atmosphere would be about –19°C, but 14°C with them. This warming was critical earlier in Earth's history when the energy output of the sun was weaker and much higher atmospheric CO_2 and CH_4 concentrations existed in the atmosphere to compensate (see the 2005 *Current Biology* Primer by Hetherington and Raven: 'The biology of carbon dioxide'). What is likely to be unprecedented geologically, however, is the speed of CO_2 emissions and consequential rate of warming via human amplification of the greenhouse effect.

It is also important to understand that there is relatively little scientific debate on the impact of CO_2 on the energy balance of the Earth. Not only is it a robust result from well established 'classical' physics, but it can also be observed in the laboratory and from satellites. Moreover, there is relatively little debate that the increases in radiatively active gases that have occurred in the past few centuries have been caused by humankind's activities. The main scientific debate is associated with the exact magnitude and pattern of climate change caused by future changes in atmospheric concentrations of greenhouse gases.

Past changes in climate

We know about climate variability and trends in climate over the past few centuries in reasonable detail thanks to surface-based instrumental records and, more recently, satellites. This can be extended further back in the past by compiling and calibrating 'proxy' measures for environmental conditions, such as the width of tree rings. The inherent short-term chaotic fluctuations and the inter-annual variability that exists within the climate system, together with the impact of solar variability and random volcanic perturbations (Figure 2) and uncertainties associated with proxy-based reconstructions and historical records, make the detection of a human fingerprint on the climate system a statistical question. Because of this 'noise', only in the past few decades has it been possible to identify unequivocally the surface warming trend due to increasing greenhouse gases. Temperature changes in the early part of last century may well have been part of the natural variations, whereas the warming seen in the last 50 years is difficult to explain unless one includes the effects of increasing greenhouse gases (Figure 2).

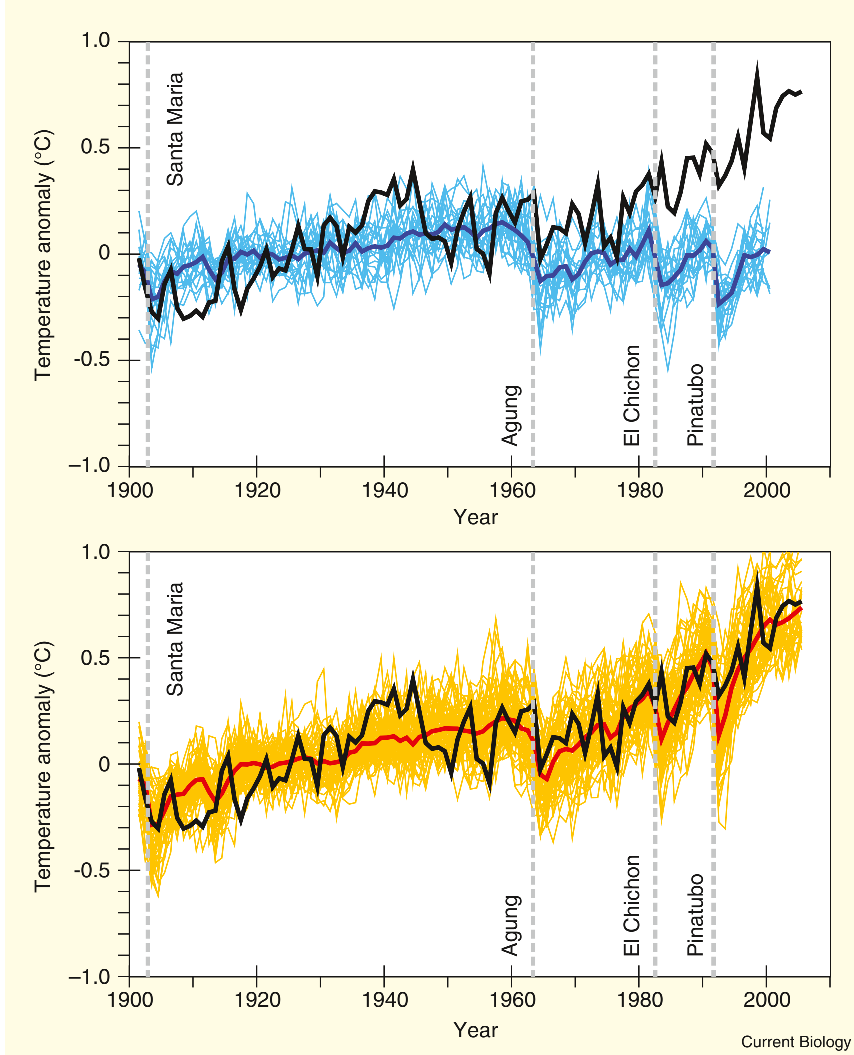

Figure 2. Comparison between observed and model-predicted global mean surface temperatures since 1900.

The upper panel shows the individual predictions of a range of atmospheric GCMs (light blue) when including only solar variability and volcanic eruptions as external forcings, with the mean of the models in dark blue. The lower panel shows the individual predictions of the same GCMs (yellow) but with the effect of increasing greenhouse concentrations in addition to solar variability and volcanic eruptions and with the model mean in red. In both panels the instrumental observations from 1900 to present are shown in black. All temperatures are plotted as anomalies relative to the period 1901–1950. Major eruptions are marked with grey dashed lines and labeled. Adapted from IPCC (2007).

Predicting climate and climate change

Unlike many areas of science, it is generally impossible to perform 'experiments' with our planet (although some scientists have described the addition of CO_2 as a fascinating global science experiment!). Instead, we have to rely on computer models as our analytical tools and experimental laboratories for helping understand the workings of the climate system and for predicting future climate change. The most important models are General Circulation Models ('GCMs'), which represent our best physical understanding of how the climate system works. They use this physical understanding to simulate the primary processes by which energy and water are redistributed on Earth. It is not possible to keep track of the energy and position of every single molecule, so the atmosphere and ocean are divided up into a three-dimensional grid, often of tens of thousands of different boxes. Each box keeps track of average properties: temperature, moisture content (salinity in the ocean), the direction and speed of winds (and currents), and the amount and properties of clouds, amongst other things. Each box interacts with adjoining boxes as well as across the interface between ocean and atmosphere. Today's GCMs often also try and estimate the growth of plants on land and phytoplankton in the ocean and how this affects the surface energy budget. Models may further account for the cycling of carbon between the different reservoirs and may represent more than one trophic level in marine ecosystems.

Much of the basic physics of the climate system can be represented explicitly in models — the equations that govern the ocean and atmospheric circulation are based on fundamental fluid dynamics which can be ultimately traced back to Newton's Laws of motion. However, the complexity of many, particularly biological, processes must be approximated and the biological equations used often take the form of an empirical fit to experiments. In addition, processes occurring on scales smaller than the size of the model grid have to be approximated by simple physical and empirical representations. The state of the climate system is then 'solved' in the computer program by making consecutive small (perhaps only 30 minutes long) steps forward in time until a stable long-term mean climate state is achieved.

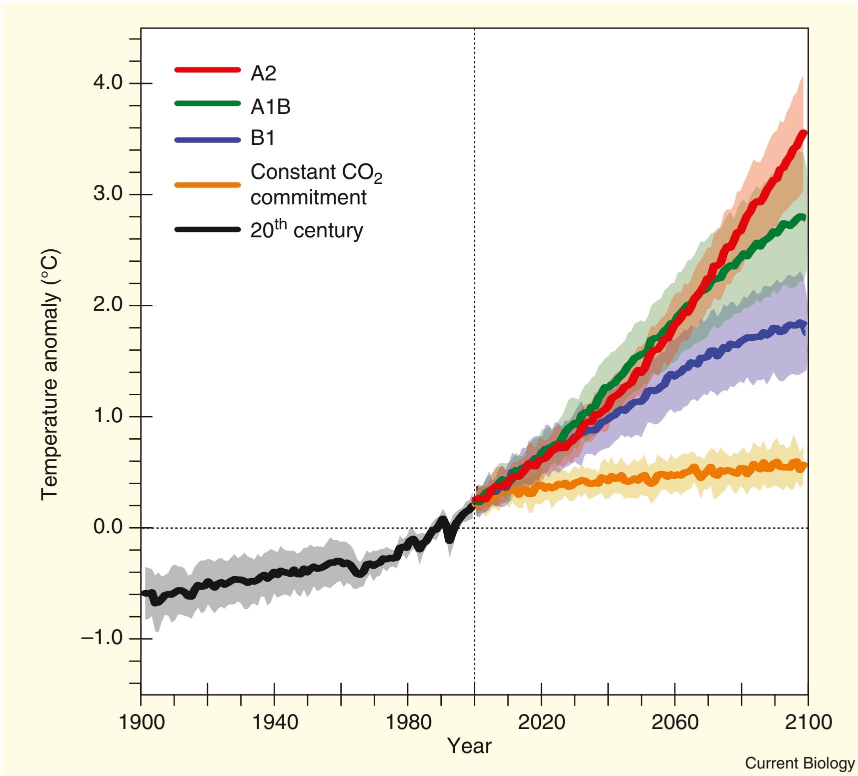

Figure 3. Multi-model means of global average surface warming, relative to the period 1980–1999.

Shown is the warming trajectory for the SRES CO_2 emissions scenarios (which represent different 'storylines' of economic and social development and energy production and usage up until the year 2100: A2 (red), A1B (green), and B1 (purple)), as well as the warming that has already been 'programmed in' to the climate system (orange) — the further warming that would occur even if atmospheric CO_2 was immediately stabilized at present-day concentrations. Also shown is the historical warming (grey). Solid lines show global temperature averaged across the models, while the shading represents ±1 standard deviations from the mean. Adapted from IPCC (2007).

To be reasonably confident in the future predictions of climate models, they must be validated — that is, shown to be capable of successfully reproducing observations. Foremost amongst observational targets is the historical surface temperature record (Figure 2). Despite differences in the number of boxes and the details of how processes such as cloud formation are represented, GCMs all agree that the temperature signal resulting from natural phenomena alone, such as volcanic eruptions and variability in the activity of the Sun, produce a very poor fit to instrumental observations. Only when enhanced greenhouse warming due to increasing atmospheric concentrations of CO_2 (and cooling due to the industrial emissions of reflective sulphate aerosols) are taken into account is the instrumental record reasonably reproduced.

Future climate

In the most recent assessment by the Intergovernmental Panel on Climate Change (IPCC), if nothing is done to limit CO_2 emissions, average surface air temperatures are predicted to increase a further 3–4°C by the end of this century (Figure 3). However, commonly quoted global and annual mean values disguise important regional and seasonal differences, with continental interiors warming more strongly than coasts and oceans, and winters warming more than summers. Summertime sea-ice cover in the Arctic is projected to progressively shrink and is likely to disappear entirely within the next few decades. Loss of the high albedo sea-ice cover will lead to further warming in a positive feedback with climate. A contraction in snow pack persistence is also projected, with important consequences for summertime water supply in places such as western Canada, Peru and the Himalayas, because melting of snow accumulated during the winter acts to even out river flow during the year.

Another key facet of climate change concerns rainfall. Warmer air can hold more moisture according to the Clausius–Clapeyron relation. In general this will equate to more rainfall. However, concurrent changes in circulation, evapotranspiration and water availability in soils will produce a complex and seasonal pattern of change. For instance, high latitudes are expected to receive increases in the amount of precipitation in the future, particularly during the winter months, while many currently arid and semi-arid regions on Earth can expect further decreases in rainfall, particularly during the summer.

The 3–4°C temperature range associated with a single CO_2 emissions scenario (A2) reflects differences between GCM models, particularly concerning the response of clouds in regulating the direct impact of increasing greenhouse gas concentrations. The greatest uncertainty in future climate change, however, is due to the unpredictability of collective political and economic decisions in the future. Depending on the choices made, it may be possible to restrict the additional global mean temperature increase by the end of the century to under 2°C (scenario B1) or even much less. But this would require rapid and immediate changes in energy generation and consumption globally. Improved understanding of the consequences of climate change for organisms and ecosystems will be critical in informing this debate and defining thresholds of 'dangerous' climate change that must be avoided.

Further reading

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